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16. ABSTRACT

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LIMNOLOGY OF SHAGAWA LAKE, MINNESOTA, PRIOR TO REDUCTION OF PHOSPHORUS LOADING

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Keywords: Shagawa Lake, Limnology, phosphorus Loading

Abstract

Various limnological parameters have been measured in Shagawa Lake, a culturally eutrophic lake in northeastern Minnesota, from 1970-1972. These included temperature; specific conductance; dissolved oxygen; alkalinity; pH; total and orthophosphate phosphorus; nitrate, nitrite and ammonia nitrogen; chlorophyll *a*; transparency; major cations; and selected trace elements. The lake exhibited many characteristics of high productivity. Concentrations of chlorophyll *a* reached 60 μg/l during summer months and were reflected in pH values in excess of 9. Anaerobic conditions developed during both summer and winter and, during these intervals, large pools of available nutrients developed in the lower waters. Manganese and iron concentrations varied greatly as a consequence of changes in the oxygen regime. Major cations and other trace elements showed no yearly pattern.

Introduction

The productivity of lakes is particularly sensitive to changes in the supply of critical nutrients which often originate from urban wastes. In many cases, high levels of productivity result from an increased supply of a nutrient or nutrients from diffuse sources. However, instances occur in which a point source supplies the unnatural levels of nutrient(s). In order to demonstrate that reduction of a particular nutrient supply from a point source would reduce the trophic state of a eutrophic lake, the City of Ely, Minnesota, recently constructed a tertiary wastewater treatment plant to serve this community of 5,000 people. Before construction, Ely had for years discharged to nearby Shagawa Lake wastewater subjected first only to primary and in later years to secondary treatment. The tertiary wastewater treatment plant, which commenced full operation in April 1973, is designed to reduce the phosphorus content of the secondary effluent by 99 percent to 0.05 mg/l or less. This paper presents some of the limnological characteristics of Shagawa Lake as they existed prior to the construction of the tertiary wastewater treatment plant. A previous paper (Malueg, *et al.*, 1975) deals with the water, phosphorus, and nitrogen budgets of the lake.

Materials and methods

Physical, chemical, and biological parameters were monitored weekly or biweekly for three years at 1.5 m depth intervals at three sampling stations (Figure 1). Data presented in this paper represent only one sampling station, Brisson's Point. The bathymetric map was prepared from depths determined during a sounding survey on 18-21 August, 1972 using a Raytheon Model DE 719 Fathometer.*

Temperature, specific conductance, pH, and dissolved oxygen were measured *in situ* with a calibrated Martek Mark II water quality analyzer (Martek Instrument Inc., Newport Beach, California). Specific conductance was corrected to 25°C according to Environmental Protection Agency (EPA) methods (1971). Water transparency was measured with a black/white 20 cm Secchi disc.

Water samples were collected with a 4-liter PVC Van Dorn sampler and, during 1970 and 1971, were preserved with mercuric chloride (final concentration 40 mg/l) and shipped to the EPA, Pacific Northwest Environmental Research Laboratory, at Corvallis, Oregon, for analysis.

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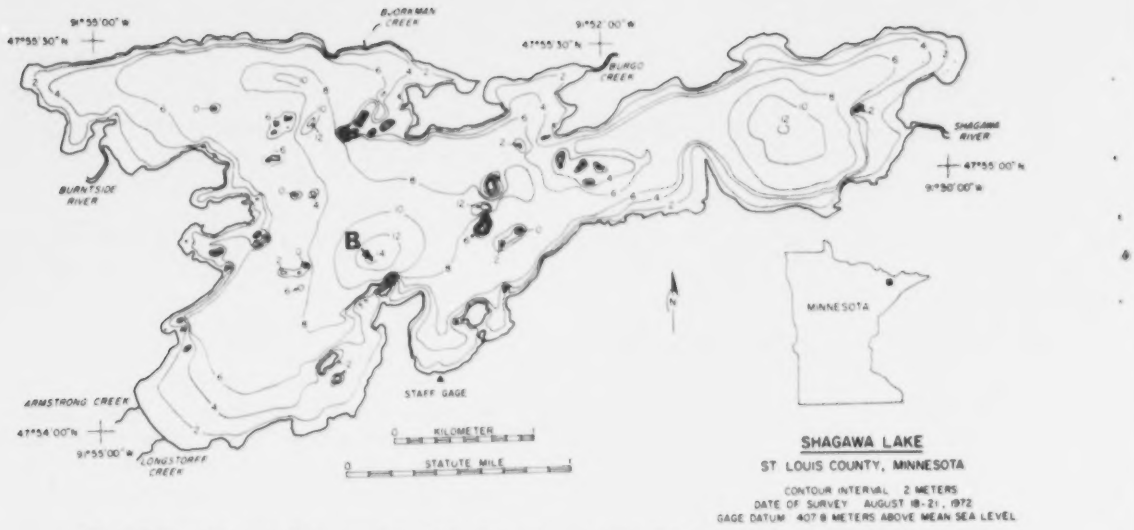

Fig. 1. Bathymetric map of Shagawa Lake. Only observations at station B (Brisson's Point) are reported herein.

During 1972, all analyses, except those for trace metals which were done at Corvallis, were performed at Ely on unpreserved samples shortly after collection. Analyses were performed using EPA methods (1971) or Standard Methods (1965); chlorophyll *a* was measured in accordance with UNESCO Methods (1966). Parameters measured and methods of analysis are summarized in Table 1.

Major cation (Ca^{++}, Mg^{++}, Na^{+}, K^{+}) and trace metal observations were obtained quarterly at three depths: 0, 6 and 12 m. These observations are reported for only 1972. Trace metal samples were preserved by adding 25 ml of concentrated HNO_3 to each liter of sample prior to shipment to Corvallis.

Table 1. Summary of Analytical Methods.

Chemical Parameter	Method of Measurement
Ammonia nitrogen	Automated indophenol blue (EPA, 1971).
Calcium, magnesium, potassium, sodium	Atomic absorption spectophotometry (EPA, 1971).
Carbonate alkalinity	Sulfuric acid titration to pH 5.1 end point indicated electrochemically (Standard Methods, 1965).
Chlorophyll a	Acetone extraction (UNESCO, 1966).
Dissolved reactive silicate	Silicomolybdate complex reduced by ascorbic acid (EPA, 1971).
Nitrate + nitrite nitrogen	Automated cadmium reduction followed by diazotization (EPA, 1971).
Orthophosphate phosphorus	Murphy-Riley, ascorbic acid (EPA, 1971).
Oxygen	Modified Winkler (EPA, 1971).
pH	Electrochemical (EPA, 1971).
Total phosphorus	Persulfate oxidation followed by orthophosphate analysis (EPA, 1971).
Trace metals	Atomic absorption spectrophotometry, concentration by evaporation (EPA, 1971).

Morphometry and hydrology

Shagawa Lake was formed during the retreat of the Wisconsin Glacier approximately 10,000 years ago. It is characterized by three 'deep' basins of about 12 m (Figure 1), an otherwise flat bottom at about 6-8 m, abrupt sides, and a moderately rough shoreline. Numerous small islands and submerged rock outcroppings occur throughout the lake. The geological history of the lake and its environs has been described by Zumberge (1952).

The surface area of the lake is 9 km^2; the volume is 53 x 10^6 m^3; and the mean depth is 5.7 m. Approximately 80 percent of the lake volume occurs above the mean depth (Figure 2). Other pertinent morphological characteristics are summarized in Table 2.

The one major tributary, Burntside River, is the outlet of nearby oligotrophic Burntside Lake. It enters the western end of Shagawa Lake, providing approximately 70 percent of the yearly inflow of water. Several minor tributaries drain the surrounding forested region and account for another 20 percent of the water input. The one outlet, Shagawa River, is located at the eastern end of the lake. The wastewater treatment plant is located midway along the southern shore and supplies about 2 percent of the water input. The water level of the lake varies less than one meter throughout any one year.

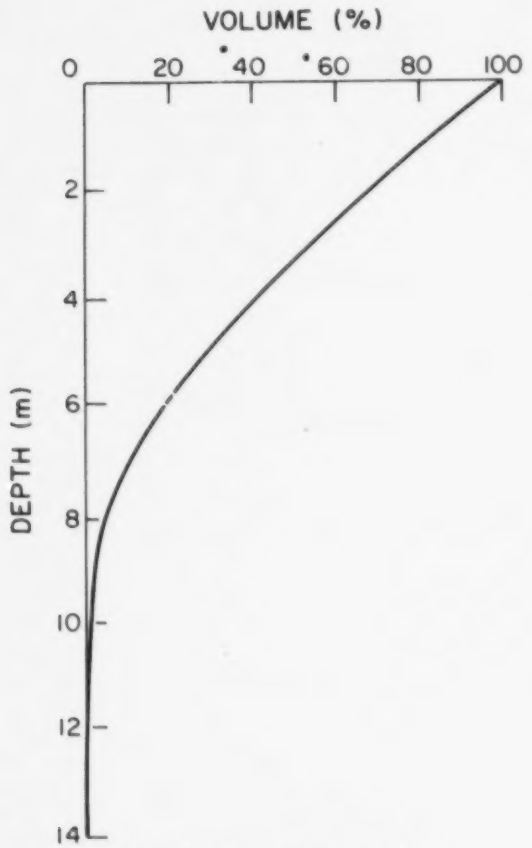

Fig. 2. Volume hypsographic curve of Shagawa Lake.

Table 2. Morphometric Characteristics of Shagawa Lake.

Maximum length:	6.58 km
Maximum width:	2.90 km
Maximum depth (Zm):	13.7 m
Mean depth ($\bar{Z}$):	5.7 m
Area:	9.24 km^2
Volume:	53 x 10^6 m^3
Shoreline length:	34.13 km (includes 5.15 km of island shoreline)
Development of shoreline:	3.17
Development of volume:	1.24
$\bar{Z}/Zm$:	0.42
Altitude of lake mean level:	407.7 m

The mean hydraulic residence time was less than one year but ranged from two months during high runoff periods to about two years during low-flow winter months. The phosphorus retention time was approximately 0.5 yr.

An early survey of the bottom sediments in 1937 indicated that the bottom was composed of 70 percent muck, 29 percent sand, and the remainder larger particles (Moyle, 1957). A recently completed survey (Waddington and Wright, 1974) indicates that generally the sediments of near-shore areas are very sandy with little organic matter, that the sediments of the deeper plains are composed of fine algal biopel and silt-sized particles and sediments of the deep holes are composed of algal biopel and clay-sized particles. The sediment of the plains and holes is composed primarily of organic material.

Results

Temperature

The three-year temperature profiles provide a fairly consistent year-to-year picture of the thermal regime (Figure 3). Surface temperatures reached a maximum of about 22°C and bottom temperatures, nearly 20°C. After ice breakup, surface temperatures rose rapidly to their maximum values; a mixed layer formed immediately and deepened throughout the summer, extending to between 5 and 6 m in 1972 (Figure 5). Occasionally the lake mixed completely, responding to passage of cold fronts or wind storms. Fall circulation commenced in late August, and the lake was well mixed by mid-September. Shagawa Lake was ice-covered approximately five months a year; dates of freeze-up and ice-out are sum-

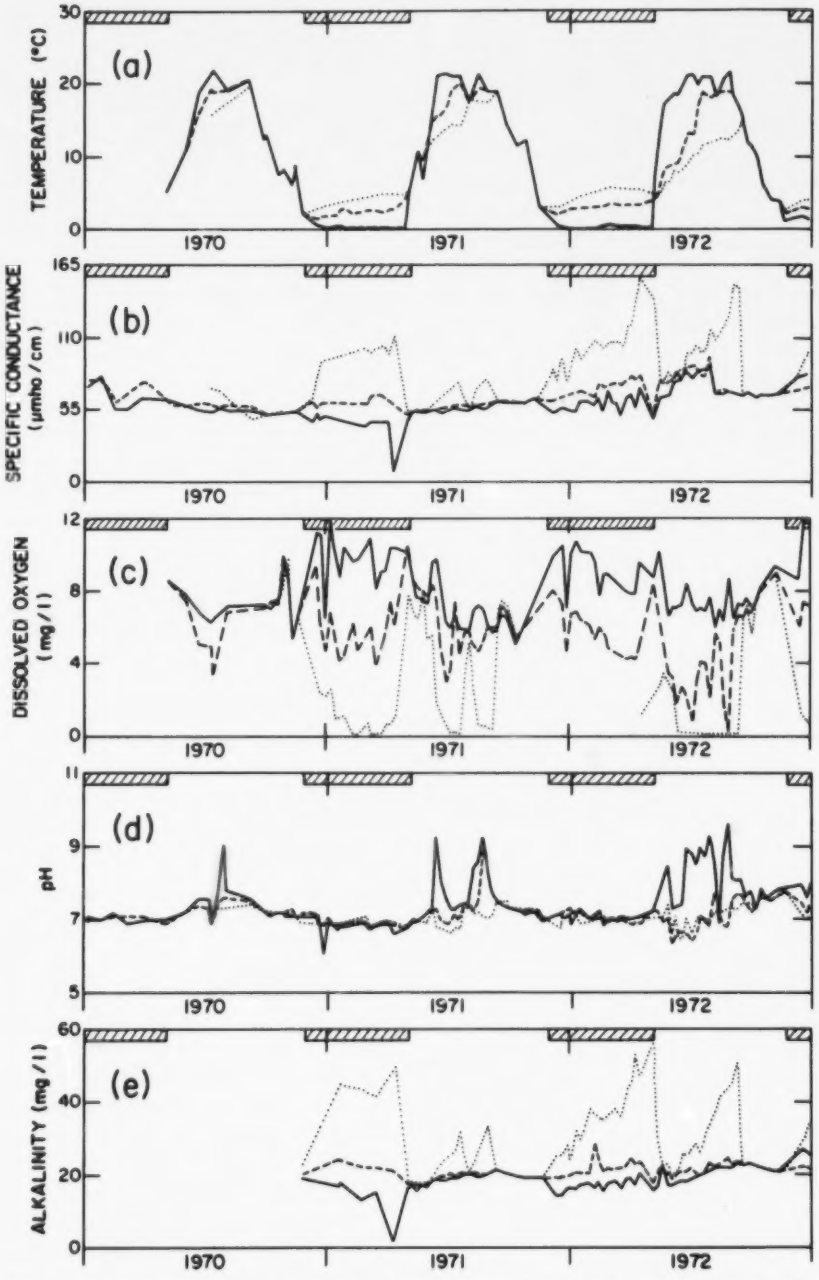

Fig. 3. Three-year profiles of (a) temperature, (b) specific conductance, (c) dissolved oxygen, (d) pH, and (e) alkalinity. ____ Surface; _ _ _ _ 6 m; .... 12 m. Cross-hatching indicates ice cover.

Table 3. Dates of Ice-out and Freeze-up in Shagawa Lake, 1970-1972.

Year	Ice-out	Freeze-up	Days of Open Water
1970	30 April	23 November	208
1971	1 May	21 November	207
1972	10 May	15 November	190

marized in Table 3. Maximum ice thickness was usually about 0.6-0.8 m. Inverse stratification developed after ice cover. Temperature increased with depth to above 5° C at the bottom of the deepest holes.

Specific conductance

The generally low specific conductance associated with soft-water lakes was evident for Shagawa Lake (Figures 3 and 5). An average of about 60 μmho/cm occurred over the three-year period during fall overturn, but there was a distinctive upward trend in the fall mean value during the three-year period. Stratification developed during winter months beneath the ice cover, while the mixed layer of the epilimnion was evident during summer months (Figure 5). Specific conductance values slightly higher than 160 μmho/cm occurred in the deeper holes just prior to ice breakup, while values less than 10 μmho/cm were recorded at the same time just below the ice cover. Except for these anomolously low values, which may have been caused by snow-melt infiltration, specific conductance rarely dropped below 50 μmho/cm.

Dissolved oxygen

The dominant feature of the dissolved oxygen profiles was the anoxia below 7 m during both winter and summer months (Figures 3 and 5). Only during and shortly after periods of circulation were the deeper waters oxygenated. Near anoxic conditions (< 0.5 mg/l) were observed at depths as shallow as 6 m in mid-summer. During summer months, a high degree of stratification occurred between the mixed layer and the anoxic deeper waters; the dissolved oxygen concentration often decreased from near saturation values to < 0.5 mg/l in 3 m.

pH

Over the three-year period, pH displayed cycles responding to biological activity; minimum values of slightly less than 6.5 occurred in deeper waters during June 1972, while surface water values of slightly greater than 9.5 were reached during periods of high productivity (Figures 3 and 5). High values were occasionally observed as deep as 3 m in 1970 and 1971 and a generally high pH level was evident throughout most of the summer months of 1972 in the upper 3 m. The interval during which high pH values occurred was longer in 1972 than in previous years.

Alkalinity

In general, low alkalinity values were about 15 mg/l and high values were slightly in excess of 60 mg/l with lowest values approaching zero under ice cover just before ice breakup (Figures 3 and 6). High values occurred below 9 m and corresponded to anoxic periods, while surface values were approximately 20 mg/l during similar intervals. The average concentration during fall circulation was about 22 mg/l. Stratification was evident through the entire water column during ice cover but only below 7 m during summer months.

Total phosphorus

Total phosphorus concentration in the surface water (less than 6 m) ranged between 0.025 and 0.1 mg/l (Figures 4 and 6); the minimum values occurred in mid-June and in mid-winter, and the maximum values occurred during late August and early September. Bottom concentrations displayed extreme ranges; maximum values observed were greater than 2 mg/l. These high values are associated with periods of anoxia during both summer and winter.

Orthophosphate phosphorus

Extremely high concentrations of orthophosphate phosphorus, approaching 1 mg/l, have been observed in the deeper water associated with the winter and more especially the summer periods of anoxia (Figures 4 and 6). These constitute a large portion of the total phosphorus measured during this interval. Surface concentrations were generally near the lower detectable limit during summer months down to depths in excess of 5 m. During 1971, high surface values (near 0.02 mg/l) were observed during most of the summer months. The orthophosphate concentration during winter months rarely exceeded 0.025 mg/l in the surface waters; however, this level is sufficient to support a substantial spring bloom of algae.

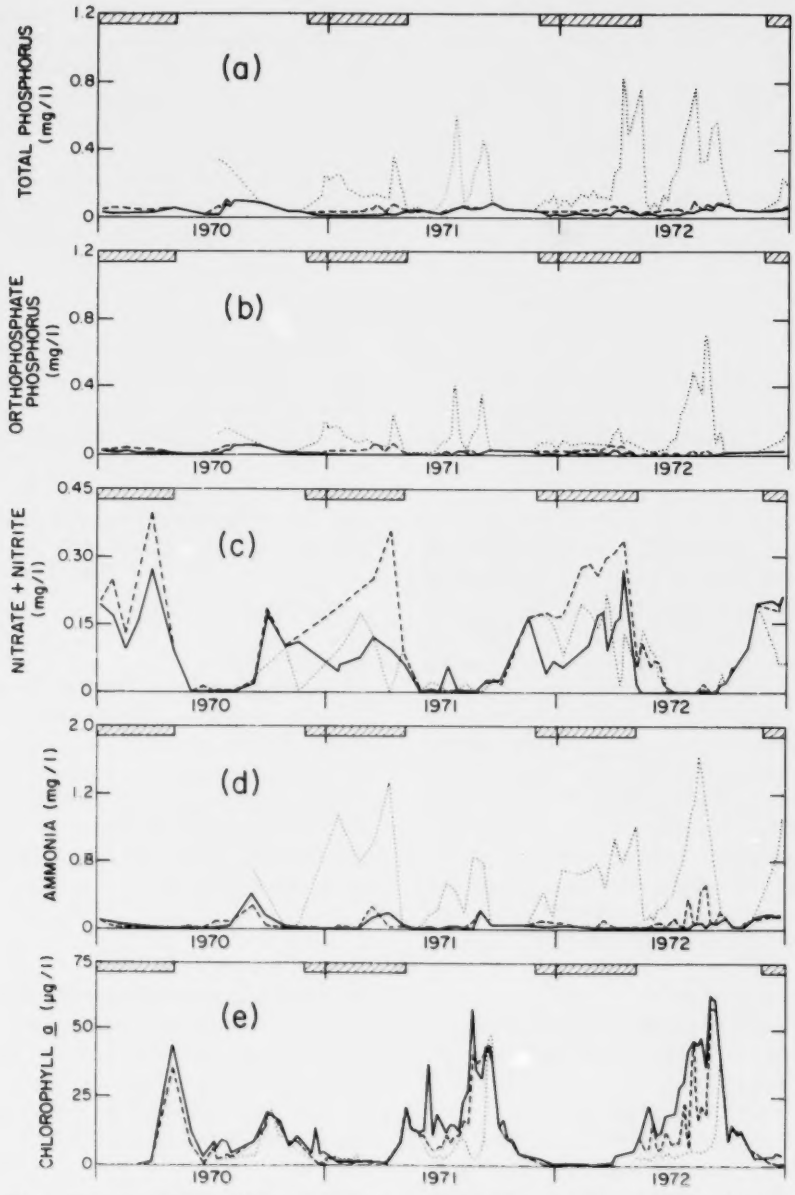

Fig. 4. Three-year profiles of (a) total phosphorus, (b) orthophosphate phosphorus, (c) nitrate + nitrite nitrogen, (d) ammonia nitrogen, and (e) chlorophyll *a*. ____ Surface; _ _ _ _ 6 m; .... 12 m. Cross-hatching indicates ice cover.

Nitrate + nitrite nitrogen

Nitrate + nitrite nitrogen concentrations were $<$ 0.01 mg/l in both surface and deeper waters during summer months (Figures 4 and 6), indicating depletion by algae in surface waters and reduction associated with anoxic conditions in deeper waters. An extensive buildup of nitrate

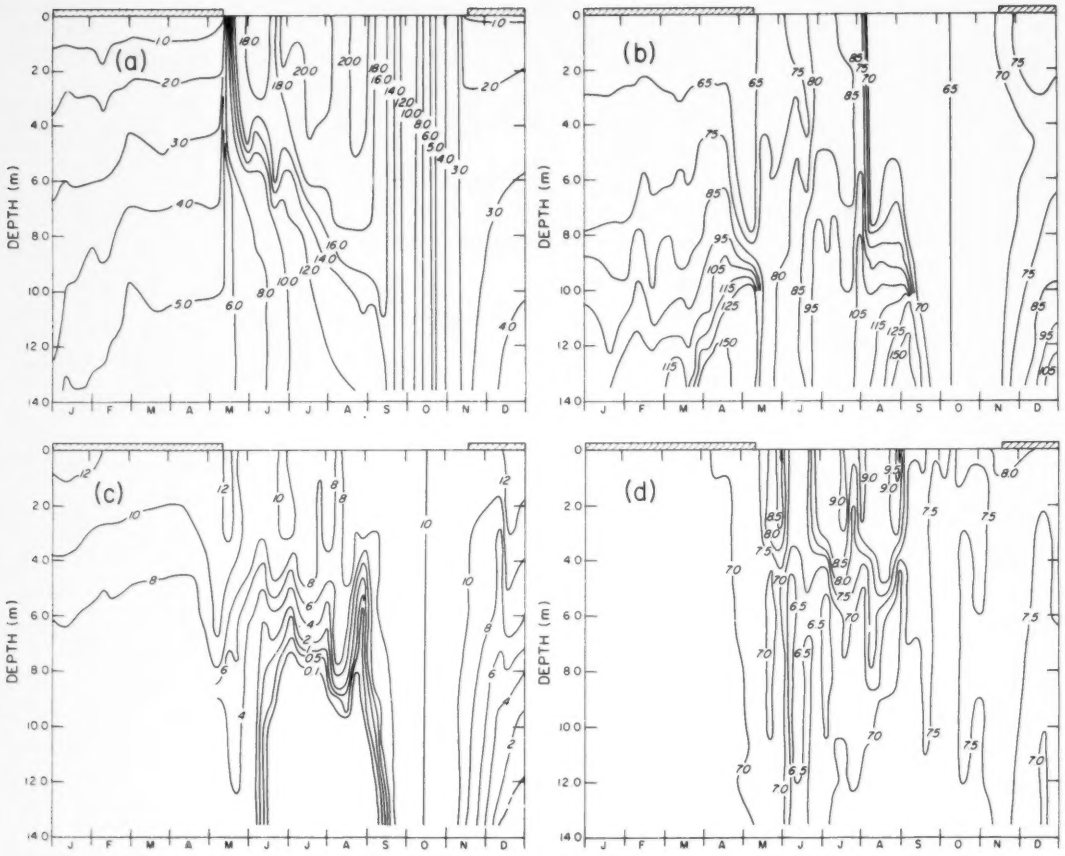

Fig. 5. Isopleths of (a) temperature (°C), (b) specific conductance (μmho/cm), (c) dissolved oxygen (mg/l), and (d) pH for 1972. Cross-hatching indicates ice cover.

+ nitrite nitrogen occurred during fall circulation and was probably the result of oxidation of ammonia nitrogen found in high concentration in bottom waters prior to fall circulation and the oxidation of organic material formed during the summer plankton algal bloom. During ice cover, values exceeded 0.3 mg/l in the bottom waters and surface values reached 0.2 mg/l. A general decline was observed during spring and was associated with spring algal activity.

Ammonia nitrogen

Ammonia nitrogen concentrations were high in deep water, especially during anoxic intervals when values near 2 mg/l were obtained (Figures 4 and 7). Surface values were generally low, but reached maxima of about 0.1 mg/l during spring under ice cover and again prior to and during fall circulation. During most of the algal growing season, surface values were near the lower detectable limit, but toward the end of August, concentrations began to increase.

Chlorophyll a

Chlorophyll *a* concentrations began to increase during the spring prior to ice breakup and reached a spring maximum of about 25 μg/l (Figures 4 and 7). A decline in concentration followed, usually reaching a minimum in June of about 10 μg chlorophyll *a*/l, although surface values often remained high. A summer bloom developed, usually commencing in late June or early July and culminating in average chlorophyll concentrations of

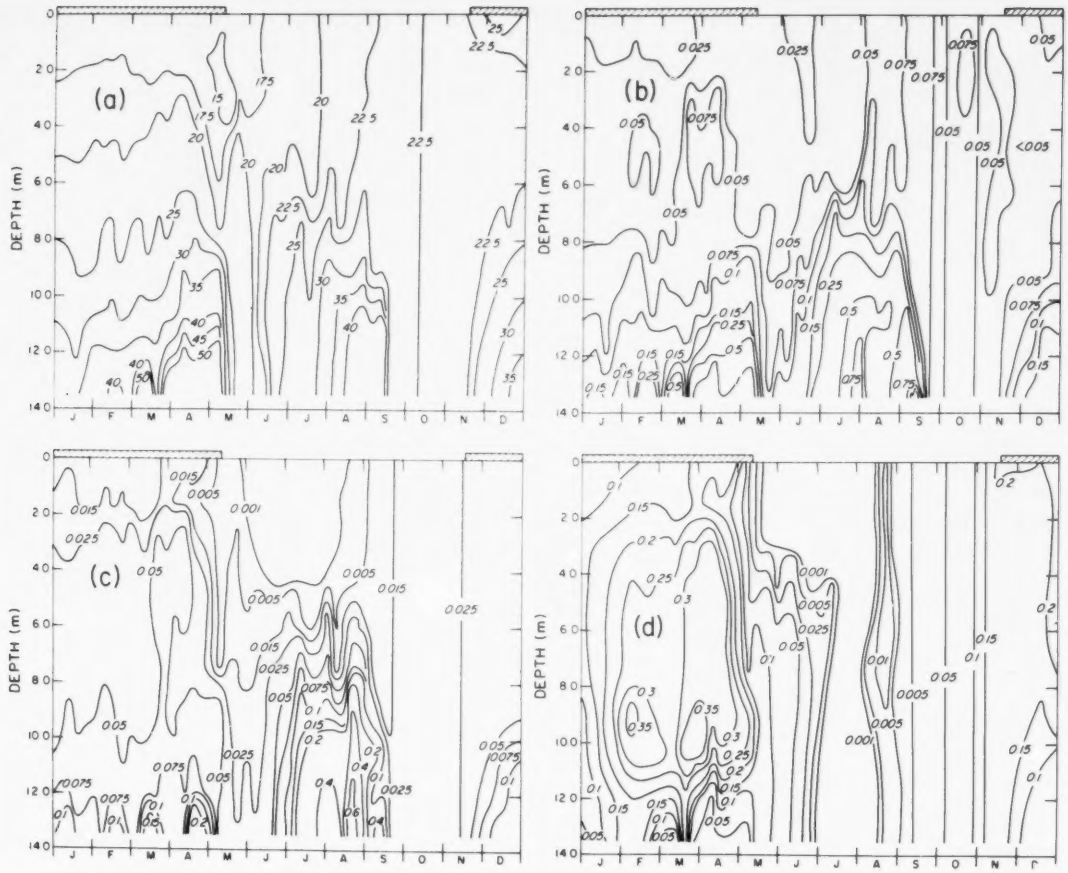

Fig. 6. Isopleths of (a) alkalinity (mg/l), (b) total phosphorus (mg/l), (c) orthophosphate phosphorus (mg/l), (d) nitrate + nitrite nitrogen (mg/l) for 1972. Cross-hatching indicates ice cover.

about 60 μg/l over the euphotic zone during late August or early September. Concentrations rapidly declined to low winter levels during late September and October. In 1970 the general trend was reversed when high concentrations of chlorophyll *a* were attained during spring months and considerably lower levels during the summer bloom. The summer months of 1970 differed from those of 1971 and 1972 in that rainfall was unusually heavy.

Algae

The succession of algal groups through the ice-free season is fairly typical of that of temperate lakes. In 1972, the pattern of succession in Shagawa Lake was a spring bloom of Chlorophyceae dominated by a flagellate, *Chlamydomonas* sp., which developed under the ice, followed by a bloom of Bacillariophyceae dominated by *Synedra ulna* and *Asterionella formosa*. During June, when algal biomass was relatively low, the Myxophyceae began to increase and dominated throughout the summer. The coccoid, *Coelosphaerium naegelianum*, and the filamentous blue-green algae, *Aphanizomenon flos-aquae* and *Anabaena circinalis* were most dominant. Increases in both Chlorophyceae and Bacillariophyceae also occurred; small numbers of Dinophyceae, mainly *Ceratium hirundinella* appeared. In early fall Bacillariophyceae, composed of *Stephanodiscus niagarae* and *Melosira granulata*, again dominated the algal community.

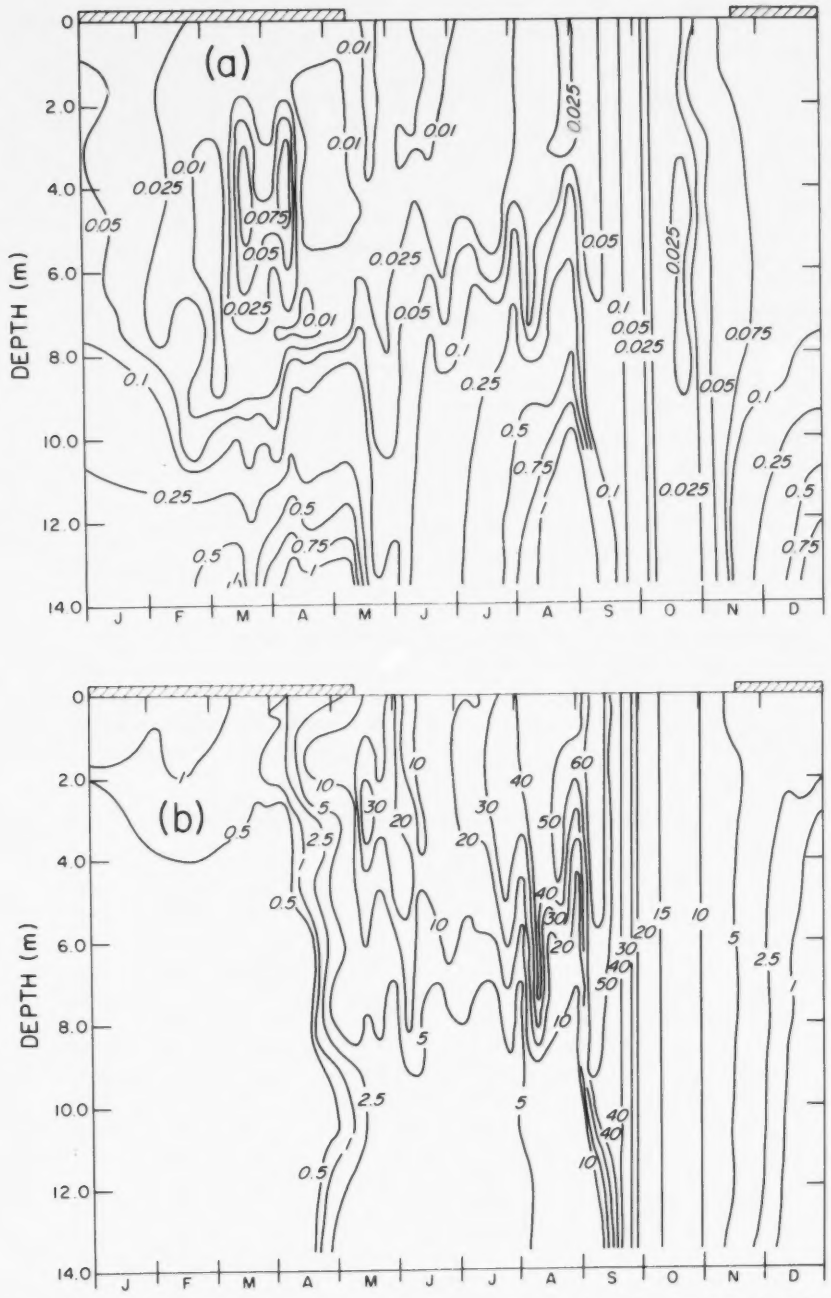

Fig. 7. Isopleths of (a) ammonia nitrogen (mg/l) and (b) chlorophyll *a* (μg/l) for 1972. Cross-hatching indicates ice cover.

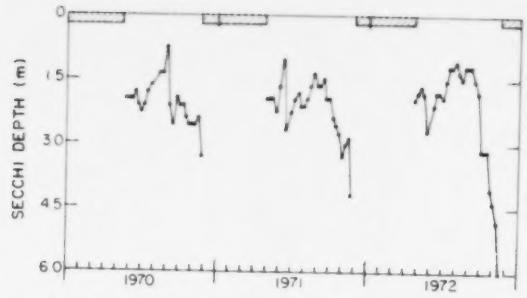

Fig. 8. Secchi depths for the three-year interval. Cross-hatching indicates ice cover.

Transparency

The Secchi disc depths for the ice-free periods of 1970, 1971, and 1972 are summarized in Figure 8. The minimum Secchi depth was about 0.75 m, and the maximum was about 6 m. In general, minimum Secchi depths of about 1.8 m occurred during the summer months, although during the August-September bloom, values less than 1.5 m were common. Increased transparency occurred as the algal abundance declined during the latter part of fall circulation. Typically, the depth to which one percent of the surface light penetrated was about 2-3 m during the August-September bloom and about 6 m just prior to ice cover.

Table 4. Summary of Major Cation Concentrations (mg/l) for 1972.

		7 March	6 June	21 August	14 November
Calcium	0 m	-	7.0	8.3	
	6 m	14.2	8.0	8.9	9.1
	12 m	25.0	8.0	11.1	9.9
	Bright (1968)	10.2			
Potassium	0 m	-	0.5	0.6	0.7
	6 m	0.6	0.6	0.6	0.7
	12 m	0.9	0.6	0.7	
	Bright (1968)	0.78			
Magnesium	0 m	-	1.4	1.4	1.7
	6 m	2.0	2.1	2.1	2.1
	12 m	2.8	2.1	2.5	2.1
	Bright (1968)	3.04			
Sodium	0 m	-	1.4	1.4	1.7
	6 m	1.5	1.5	1.5	1.6
	12 m	2.3	1.4	1.6	1.6
	Bright (1968)	1.6			

Major cations and trace elements

There was no evident seasonal trend in 1972 in the changes in concentrations of the major cations Ca^{++}, Mg^{++}, Na^{+}, K^{+} (Table 4), although concentrations of all were highest at 12 m in March. There was also an indication of mini-

Table 5. Summary of Trace Element Concentrations (mg/l) for 1972.

		7 March	6 June	21 Aug.	14 Nov.
Aluminum	0 m	0.05	0.10	0.21	0.11
	6 m	0.05	0.20	0.26	0.16
	12 m	0.05	0.20	0.27	0.10
Cobalt	0 m	0.002	0.001	0.002	0.001
	6 m	0.002	0.001	0.002	0.001
	12 m	0.004	0.001	0.004	0.001
Copper	0 m	0.0035	0.004	0.004	0.003
	6 m	0.003	0.002	0.004	0.004
	12 m	0.0035	0.002	0.0035	0.003
	Bright (1968)	0.0062			
Iron	0 m	0.180	0.070	0.225	0.083
	6 m	0.145	0.280	0.375	0.112
	12 m	0.732	0.420	10.3	0.076
	Bright (1968)	0.094			
Lead	0 m	0.005	0.005	0.010	0.005
	6 m	0.005	0.008	0.005	0.005
	12 m	0.005	0.005	0.0075	0.005
Manganese	0 m	0.0225	0.020	0.067	0.006
	6 m	0.040	0.085	0.129	0.006
	12 m	1.1	0.135	2.22	0.005
	Bright (1968)	0.0168			
Mercury	0 m	<0.0005	<0.0005	-	-
	6 m	<0.0005	<0.0005	-	-
	12 m	<0.0005	<0.0005	-	-
Molybdenum	0 m	<0.01	<0.01	<0.01	<0.01
	6 m	<0.01	<0.01	<0.01	<0.01
	12 m	<0.01	<0.01	<0.01	<0.01
	Bright (1968)	0.002			
Silicate	0 m	4.25	-	0.35	2.05
	6 m	5.02	-	1.15	2.07
	12 m	8.70	-	3.25	2.07
	Bright (1968)	5.57			
Zinc	0 m	0.009	0.012	0.012	-
	6 m	0.008	0.007	0.013	-
	12 m	0.010	0.008	0.010	-
	Bright (1968)	0.0116			

mum values during summer. However, there are insufficient data to form a statistically valid statement. The order of abundance was $Ca^{++} > Mg^{++} > Na^{+} > K^{+}$ which is the same order of abundance observed by Bright (1968) who surveyed 19 Minnesota lakes, including Shagawa, during the fall of both 1966 and 1967. The concentrations also are not markedly different from those observed by Bright. See Table 4 for comparisons.

Trace element concentrations are summarized in Table 5. Soluble reactive silicate, although technically not classed as a trace element, is included. Its concentration was highest prior to the spring algal bloom, was low during August in surface water, and increased after fall turnover.

Iron and manganese displayed the greatest variability. The highest values for both were observed at 12 m in August during the summer period of anoxia. Both were also found in high concentrations at 12 m in March, when presumably the bottom waters were anoxic. Mortimer (1941, 1942) has discussed the control that the dissolved oxygen regime exerts over the abundances of both iron and manganese; hence, the observations are not unexpected.

There are insufficient data to determine whether the variability associated with the concentrations of the other trace elements was due to anything but sampling and analyses. The concentrations of mercury and molybdenum were at or below the limits of detectability of the analytical procedures used. Copper concentrations were about one half that reported by Bright while zinc concentrations were similar. Comparative data are unavailable for the other trace elements.

Discussion

Shagawa Lake exhibited many of the features which would classify it as eutrophic. Sawyer (1947) indicated that the lakes near Madison, Wisconsin could be expected to produce nuisance algal blooms if the concentration of inorganic phosphorus exceeded 0.01 mg/l and the concentration of inorganic nitrogen exceeded 0.3 mg/l at the time of spring overturn. Vollenweider (1968) suggested that a lake would be 'in danger with regard to its trophic level' if springtime concentrations of assimilable phosphorus compounds exceeded 0.01 mg/l and inorganic nitrogen compounds exceeded 0.2-0.3 mg/l. In Shagawa Lake the springtime concentrations of orthophosphate phosphorus were generally greater than 0.02 mg/l and those of inorganic nitrogen were about 0.2 mg/l.

Vollenweider also suggested that the loadings of phosphorus and nitrogen to lakes normalized to mean depth and surface area might be used as indicators of the trophic state of a lake and that mean annual loadings of 0.13-0.20 g $P/m^2/yr$ and 2-3 g $N/m^2/yr$ would be likely to produce noxious conditions in lakes the size of Shagawa. Malueg, *et al.*, (1975) reported that the mean annual loadings for phosphorus and nitrogen to Shagawa Lake during the interval 1967-1972 were 0.73 g P/m^2 and 7.64 g N/m^2 per yr, well above the threshold values indicated above.

Vollenweider further suggested that lakes of high trophic level attain annual primary productivity levels of 150-200 g C fixed/m^2 and often exceed this value. Megard & Smith (1973) observed that mean daily productivity in Shagawa Lake between early June and late October, 1970 was 1.2 g C/m^2/day or about 180 g C/m^2 for the five-month interval. This interval excludes the usual spring bloom occurring in May, and, therefore, the measure is an underestimate of the annual productivity; yet, the value is within the level suggested by Vollenweider as being a result of high trophic state.

Malueg *et al.*, (1975) reported that approximately 80 percent of the phosphorus and 24 percent of the nitrogen entering the lake were attributed to wastewater from Ely, but only 2 percent of the water entering the lake was wastewater, the remainder entering primarily from nearby oligotrophic Burntside Lake. Powers *et al.*, (1972) and Smith (1973) demonstrated that secondarily treated wastewater, and particularly phosphorus in the secondarily treated wastewater, stimulated algal growth. They added increments of Ely wastewater (as well as wastewater treated for phosphorus removal and spiked with various increments of phosphorus) to Burntside River water and observed the growth response of both selected species of algae and natural algal communities. They concluded that the phosphorus supplied by the wastewater of Ely was responsible for the eutrophic state of Shagawa Lake.

As a result of the high level of fertility and associated high levels of algal activity, several other limnological parameters showed marked differences from those observable in similar but less fertile systems. Most of these differences occurred as a direct result of increased algal productivity. Dissolved oxygen reached anoxic levels during both summer and winter in the deeper waters, and when not anoxic, conditions rapidly approached

anoxia, except during periods of circulation. Deeper water nutrient levels (nitrogen and phosphorus) were extremely high; highest values occurred in conjunction with anoxic conditions. Secchi depths were shallow (1.5 m) during periods of greatest algal activity and deeper (4 m) when algal activity was lowest. Typically, pH values were slightly greater than 7--not unusual in lakes in this region (Bright, 1968). During periods of highest algal activity, pH values often exceeded 9.5 in the euphotic zone.

The change in the trophic state of Shagawa Lake from one of presumed oligotrophy to eutrophy is an excellent example of the alteration which man can induce in natural systems. The Shagawa Lake watershed was sparsely populated prior to the late nineteenth century. Associated with the discovery of iron deposits in the late 1880's and the increase in logging in the area, the community of Ely developed. Ely was incorporated in 1891 with a population of 901 and reached a population of about 6100 by 1930, from which time a gradual decline occurred to its present level of approximately 5000. Wastewater was initially discharged directly to the lake; primary treatment was instituted in 1912 and secondary treatment, in 1954.

Although no quantitative data are available to document the changes in biological activity in the lake associated with increased population pressure, several indirect lines of evidence suggest that Shagawa Lake responded rapidly to increased nutrient loadings from Ely. Verbal reports indicate that heavy blooms existed at the turn of the century and thereafter. By the 1930's, bacterial activity was such that Shagawa Lake water was unsafe for human consumption; in 1932 a pipeline was constructed to obtain water from nearby Burntside Lake. The few chemical measurements available from Shagawa Lake indicate that dissolved oxygen concentration in the bottom water was near zero in the summer of 1936 (Minnesota Division of Game and Fish, 1936), suggesting high levels of organic production in surface waters.

Two sediment cores obtained from Shagawa Lake provide a somewhat inconsistent picture of the trophic history of Shagawa Lake (Bradbury & Megard, 1972; Bradbury & Waddington, 1973). The interpretation of the diatom distribution from the first core was that diatoms characteristic of highly productive systems replaced those characteristic of low productivity systems when human activity increased in the area. Results from the analysis of the second core from a deeper part of the lake basin indicated that the productivity of the lake increased significantly when settlement increased, but that the lake may have been at least moderately productive historically.

An increasing awareness of the impact which inadequately treated human wastes have upon aquatic ecosystems has led to the development of tertiary wastewater treatment techniques. The application of tertiary treatment to wastewater allowed to enter Shagawa Lake is an attempt not only to prevent further deterioration of the lake and those downstream, but also to reduce the level of fertility and its associated effects within the lake.

From the evidence available so far, it is likely that Shagawa Lake was considerably less productive as recently as 1880. It is expected that its level of fertility will decrease significantly over the next several years. Application of Vollenweider's (1969) recovery model (which assumes a constant phosphorus retention time) suggests that a new steady state level should be reached in 1.5-2.5 years, at which time the total phosphorus concentration should be about 0.015 mg/l. However, because the sediments are likely to provide significant amounts of phosphorus for some time, a more gradual change is expected. Continued limnological study will provide a detailed picture of the decrease in fertility of the lake and an assessment of the role which sediments play in the metabolism of this lake.

Summary

Various limnological characteristics of Shagawa Lake, Minnesota, are reported for the interval between 1970 and 1972. These include temperature; specific conductance; dissolved oxygen; alkalinity; pH; total and orthophosphate phosphorus; nitrate, nitrite, and ammonia nitrogen; chlorophyll *a*; transparency; major cations, and selected trace elements. Most limnological properties displayed wide ranges in response to high levels of productivity. Chlorophyll *a* concentrations averaged over the euphotic zone reached maximum values of about 60 μg/l in late summer. Nitrogen and phosphorus nutrient concentrations in the euphotic zone ranged from near zero during June to values in excess of 0.2 mg/l for nitrogen and 0.02 mg/l for phosphorus during winter. Anoxic conditions developed below 7 m during both summer stratification and under winter ice cover. Specific conductance averaged 60 μmho/cm and alkalinity, 20 mg/l during fall overturn. Major cation concentrations (Ca^{++}, Mg^{++}, Na^{+}, K^{+}) showed no seasonal variability. Iron and manganese concentrations fluctuated widely as a result of

changes in oxygen concentrations. Other trace elements displayed no seasonal variability.

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